COSC460 Report:
Medium access control protocols for WDM optical networks

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Robert Mollard   Associate Prof. K. Pawlikowski[1]

[1]Supervisor

Abstract

Wavelength-division multiplexing (WDM) has emerged as the most popular technology for utilising the huge bandwidth of optical fibre.

This paper surveys medium access control protocols for the star, bus and ring WDM network topologies. The performance of two recently developed protocols, Pipelining Cyclic Scheduling Algorithm (PCSA) and Reservation/ACK/Transmission Protocol (RATP), is evaluated by stochastic simulation.

It was found that RATP's performance (measured by throughput and delay) degrades sharply with the increase in network size, making it impractical for use in metropolitan- or wide-area networks. PCSA does not suffer from this restriction, and can realise a throughput of 1. It also delivers short average packet delays, especially under light to moderate system loads.

Keywords: Optical networks, wavelength division multiplexing, medium access control.

Contents

Chapter 1

Introduction

We are moving towards a society where more and more people require fast access to information that is transmitted over networks.

Although voice traffic continues to grow steadily at about seven percent per year, which would be considered very healthy growth in many business sectors, it is the explosive growth of data traffic that has drawn people's attention. Most telecommunications carriers have reported that data traffic has already overtaken voice traffic in their fibre links and networks [27].

As increasing numbers of people start to use data networks, their usage patterns change to include high bandwidth network applications such as Java applications and streaming audio and video. This is resulting in an acute need for very high bandwidth networks — there is simply not enough bandwidth even in today's high-speed asynchronous transfer mode (ATM) networks to accommodate the huge expected growth in user data traffic [14].

Fibre-optic technology is currently the only practical solution to this problem due to its unique capabilities: incredible bandwidth of terabits per second, low signal attenuation (as low as 0.2 decibels per kilometre), low power requirement and low cost.

Wavelength-division multiplexing (WDM) is currently the technology of choice for utilising the bandwidth of optical fibre. The basic concept of WDM technology is the ability to transmit data on several different wavelengths simultaneously. With WDM, independent channels are created that operate at a few gigabits per second each — a rate that is within the limits of electronic processing speed.

If the available wavelengths are shared between the stations in the network, medium access control (MAC) protocols are required to arbitrate the access to the wavelengths.

To date, a very limited number of surveys have been performed that compare the MAC protocols available for WDM optical networks. This paper surveys the MAC protocols that have been developed for the three main WDM network topologies: star, bus and ring. The performance of two very recently developed MAC protocols, PCSA and RATP, is evaluated by simulation.

1.1 Report structure

The following chapter describes WDM technology in more detail, along with its alternatives: time-division multiplexing and code-division multiplexing. In chapter 3, medium access control protocols and their desirable characteristics are discussed. Previous work is surveyed and reviewed in chapter 4.

The network topologies star, bus and ring are covered by chapters 5, 6 and 7 respectively. Each such chapter discusses the advantages and disadvantages of the corresponding topology and briefly describes the MAC protocols available for it. The two protocols that are evaluated by simulation are discussed in additional detail. Finally, the MAC protocols are summarised in tables.

Chapter 8 describes the simulation models and experiments performed in the evaluation of the PCSA and RATP protocols. The results of these simulations are given in chapter 9, and conclusions are presented in chapter 10.

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Chapter 2

Exploiting optical bandwidth

Optical fibre has presented an enormous potential bandwidth of more than 50 terabits per second. Since the maximum rate at which an end user[1] can access the network is limited by electronic devices to a few gigabits per second, efficient optical networks that exploit the fibre's huge bandwidth require concurrent user transmissions into the network. This concurrency can be achieved by partitioning the bandwidth according to:

- Time slots, as in time-division multiplexing (TDM)
- Wave shape, as in spread spectrum or code-division multiplexing (CDM)
- Wavelength or frequency, as in wavelength-division multiplexing (WDM).

2.1 Time-division and Code-division multiplexing

Optical TDM would involve interleaving many low bit rate channels (all using the same wavelength) into a single stream of a much higher bit rate. The size of each time slot would be of the order of several picoseconds. These extremely short time slots make it very difficult for an end user to synchronise to within one time slot.

The optical TDM bit rate is aggregate rate over all the TDM channels in the system, and the optical CDM chip rate may be much higher than each end user's data rate. Therefore, the TDM bit rate and the CDM chip rate may both be higher than electronic processing speed, meaning that some part of the end user's network interface must operate at a rate that is higher than electronic

[1] Here, an "end user" may be a workstation or a gateway that accesses a lower speed subnetwork

processing speed. TDM and CDM are therefore somewhat less attractive than WDM, which does not suffer from this disadvantage [8].

2.2 Wavelength-division multiplexing

With wavelength-division multiplexing, the optical transmission spectrum is divided into a number of non-overlapping wavelength bands (or, equivalently, frequency bands), with each wavelength band representing a communication channel. These individual wavelength bands may operate at any desired rate — for example, at electronic processing speed. In this manner, the bandwidth offered by optical fibre can be exploited by allowing multiple WDM channels to exist simultaneously on a single optical fibre.

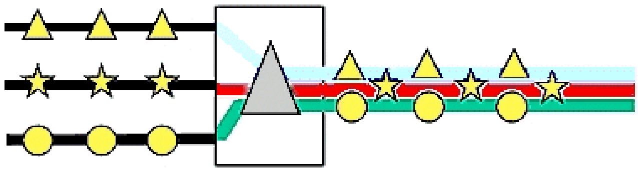

Figure 2.1: Three data channels multiplexed with WDM

The theoretical upper limit on the number of WDM channels is close to one thousand, and has recently been achieved in laboratory demonstrations [31] at Lucent Technologies. WDM systems that utilise up to 160 wavelengths for a total transmission capacity of 1.6 terabits per second are commercially available today [33].

WDM devices are easier to implement than optical TDM or CDM devices, since the components in the WDM device generally only need to operate at electronic speed rather than optical speed. As a result, many WDM devices are commercially available today. WDM line systems are already used around the world, and attention is now turning towards WDM-based local- and metropolitan-area networks.

2.2.1 WDM network classification

One can classify WDM optical networks as either broadcast-and-select networks or wavelength routing networks.

In wavelength routing networks, information is routed, switched and forwarded through the network according to wavelength. The routing can either be fixed or dynamic. To support packet switching, dynamic wavelength routing is needed. The scalability of wavelength routing architectures makes them well-suited to serve wide-area networks.

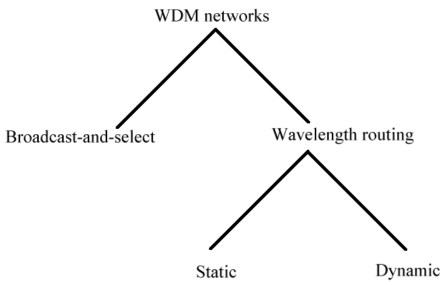

Figure 2.2: Classification hierarchy of WDM networks

In a broadcast-and-select network, a node that has information to send broadcasts this information to all the other nodes in the network. The receiver then selects this signal from the entire group of signals transmitted by, for example, using its tunable receiver to select the wavelength carrying the desired information. Problems with broadcast-and-select networks include splitting loss and lack of scalability. Broadcast-and-select architectures, which this paper focuses on, are therefore best suited to serving local- and metropolitan-area networks.

Chapter 3

Medium access control protocols

The medium access control (MAC) protocol layer exists just above the physical layer in the ISO Open Systems Interconnection model and the IEEE 802 reference model. It is designed to ensure orderly and fair access to a shared medium. It manages the division of access capacity among the different stations on the network. A good MAC protocol should be:

- Efficient. There should be high data throughput and packets should not experience large transfer delays.
- Fair. Each station should have equal access to the medium.
- Simple. The implementation of the MAC protocol should not be so complex that it requires powerful hardware or long processing times that impair performance.

These conflicting requirements have been a challenge to MAC protocol designers ever since the development of the Aloha protocol in the 1960's. A large amount of research has been performed in this area, which has led to many solutions, implementations and standards. Despite this extensive research effort, there is still a strong need for MAC research [20].

The fundamental tradeoff between efficiency and simplicity has been analysed and debated for the last thirty years. Traditionally, MAC protocols were designed to be simple. The need for speed and simplicity in the MAC layer outweighed the benefit of efficiency. However, with the incredible growth in computing speed, it is becoming plausible to design more complex MAC protocols in order to improve efficiency, such as achieving better utilisation and meeting quality of service (QoS) requirements.

The MAC problem of scheduling transmissions in a broadcast-and-select network can be posed as a matrix-clearing problem, in which a traffic matrix must be processed time slot by time slot until all entries in the matrix are clear.

Since this problem has been proven to be NP-hard, only heuristics have been proposed.

A current trend in the design of MAC protocols for WDM local area networks is to employ a centralised architecture rather than a distributed one. Requests are sent by users to a central controller that allocates bandwidth according to a given scheduling algorithm. The use of such a scheduler allows control over the bandwidth allocated to different services, and hence the provision of QoS requirements.

Many different MAC protocols have been proposed, ranging from random access schemes, fixed-access schemes such as time division multiple access, to reservation schemes where nodes reserve communication sub-channels.

Chapter 4

Previous Work

4.1 Indulska and Richards

Jadwiga Indulska and Jason Richards [19] compare the bus topologies FairNet, WDMA and nDQDB.

The performance of these protocols, measured by throughput and delay, is assessed by stochastic simulation, and the suitability of these protocols for multimedia applications is discussed.

4.2 Montgomery

Michael Montgomery gives a comprehensive survey and comparison of MAC protocols for broadcast-and-select WDM networks in his paper "A Review of MAC Protocols for All-Optical Networks" [25].

The star topology is covered in depth, and protocols for the single-folded and dual bus topologies are also discussed.

However, because it was written in 1994, later protocols such as Synchronous Round Robin are absent.

4.3 Li, Maode and Hamdi

A more comprehensive survey of MAC protocols is given by Li, Maode and Hamdi [21]. Protocols for the three most popular WDM network topologies (star, ring and bus) are compared. Written in 2000, only the most recent protocols such as Reservation/ACK/Transmission Protocol and Pipelining Cyclic Scheduling Algorithm are missing.

Chapter 5

Star Topology

A star topology (shown in Figure 5.1) consists of a number of nodes connected with bi-directional links to a central coupler.

The central coupler for a star network of N nodes can either be implemented directly in integrated form with a common coupling region, or by using $\frac{N}{2}\log_2 N$ individual 2×2 couplers.

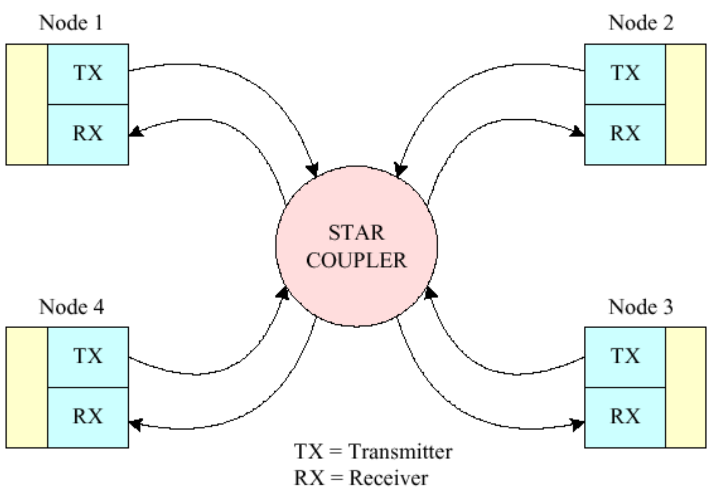

Figure 5.1: Star topology with four nodes

Unlike copper networks, optical networks are "power limited" rather than "bandwidth limited". Power limits are therefore an important consideration when choosing the physical topology for an all-optical network.

The signal power arriving at the receiver nodes in a star network decreases only slightly as the number of nodes increases: on the order of the logarithm of the number of nodes. This compares favourably with optical bus networks, where power loss is cumulative. The power efficiency of a star network ensures that it can support a greater number of stations than a bus network.

Wavelength selection in a star network can be implemented using a combination of tunable transmitters (TTs), tunable receivers (TRs), fixed transmitters (FTs) and fixed receivers (FRs). The network flexibility, cost and complexity increase with the number of tunable components. For example, in a network in which each node has a tunable receiver and a fixed transmitter, video or audio streams can be broadcast on fixed wavelengths. The users then use their tunable receiver to select the desired channel.

5.1 Demonstrators

Several demonstrators based on the broadcast-and-select star approach have been developed [26]. One of the first demonstrators was LambdaNet, which was developed by Bellcore in the late 1980's and early 1990's. LambdaNet used 18 wavelengths modulated at 1.5 gigabits per second, subsequently upgraded to 2 gigabits per second. Each node of the N stations was equipped with one fixed receiver and N fixed transmitters, one for each data channel.

RAINBOW-I was built by IBM in the early 1990's and evolved into RAINBOW-II. The network connected 32 computers using 32 wavelengths. RAINBOW-I's transmission speed rate of 300 megabits per second was upgraded to 1 gigabit per second in RAINBOW-II.

The European Research and Development for Advanced Communications in Europe program also developed a WDM star demonstrator. This was used for video applications in a BBC television studio testbed. The nodes in the network were called local routing centers (LRCs). Each LRC interconnected up to 16 electronic sources and destinations that each operated at 155 megabits per second. This gave a total LRC transmission rate of 16×155 megabits $= 2.5$ gigabits per second. The network could support a total of up to 16 such LRCs.

5.2 MAC protocols

In this chapter, MAC protocols for the star topology are described according to the following criteria:

- **Tell-and-go**

  A MAC protocol that supports this feature allows a station to inform the destination station that it is transmitting a packet, and then transmit the packet without waiting for any form of acknowledgement. This desirable feature can reduce the time taken for a packet to arrive at its destination (transfer delay). In protocols that use a reservation scheme to coordinate transmissions, a station that wishes to transmit must wait for the time it takes for a packet to make a round trip of the network.

- **Channels**

  The number of channels (wavelengths) required by the protocol, including the control channel.

- **Equipment**

  The components that are required at each station in the network.

- **Throughput**

  The normalised throughput, S, is defined as

  $$S = \frac{\lambda \overline{X}}{\sigma}$$

  where λ is the number of new packets generated per second, $\overline{X}$ is the average number of bits per packet, and σ is the transmission capacity of the network.

  When stations in the network are equipped with tunable transmitters and fixed receivers, *collisions* are possible if two or more stations send a packet to the same destination at the same time. With fixed transmitters and tunable receivers, *destination conflicts* can occur if multiple stations transmit on different wavelengths to the same destination at the same time. In this case, the destination station can only receive one of the transmissions. If the transmitters and receivers of the stations are tunable, collisions and destination conflicts are both possible.

  Collisions and destination conflicts reduce throughput since packets have to be re-transmitted. In general, MAC protocols that use a reservation scheme to prevent collisions and destination conflicts can achieve the highest throughput.

- **Processing**

  It is desirable for the MAC protocol to have low processing requirements at each node. The processing involved in monitoring a control channel that transmits packet headers for all traffic in the network can become an electronic processing bottleneck as the number of nodes in the network increases. Distributed algorithms that are executed to resolve collisions or destination conflicts also increase the processing requirements.

5.2.1 Aloha and Slotted Aloha

The well-known Aloha protocol can be modified [17] to operate in a broadcast-and-select star network where each station has a tunable transmitter and a tunable receiver. A station that has a packet to send randomly chooses a data channel and transmits a control packet containing the source, destination and channel information on the control channel. The station then immediately transmits the data packet on the selected data channel. The packet is successfully received if there was no collision on the control channel or the data channel. Although this protocol is simple, it has high processing requirements since each station must listen to all packets on the control channel. Throughput is low due to collisions. However, an advantage of Aloha is that a station can transmit a packet as soon as it receives it. Also, any number of data channels can be used. Moreover, network-wide synchronisation is not required.

Slotted Aloha [32] forces a station to wait until the beginning of a slot period before sending its packet. This reduces the number of collisions and hence improves throughput, but slightly increases the waiting time before packet transmission.

5.2.2 I-SA

The Interleaved Slotted Aloha (I-SA) [29],[30] protocol is a relatively simple protocol that does not require a large amount of processing. I-SA requires one tunable transmitter and one fixed receiver per node before information can be transferred. Each node has a single queue that buffers arriving packets if the transmitter is busy. Each transmission in I-SA consists of two phases: data packet transmission and acknowledgement transmission. During the data packet transmission phase, the transmitter transmits the packet at the head of the queue. If the packet transmission is not successful, the transmitter follows a back-off policy for retransmission.

The acknowledgement phase consists of the destination node protocol processing delay, the transmitter tuning time, and the propagation delay. This phase may be time division multiplexed among the nodes to avoid collisions when the number of nodes is more than the number of channels. An acknowledgement is sent by the destination node immediately after each data packet is received. To ensure proper handshaking, the source node will hold the channel on which the data packet was transmitted until after the acknowledgement phase is complete. This results in decreased channel utilisation, which is considered a major drawback of the protocol.

5.2.3 I-SA*

I-SA* [3] is a variation of the I-SA protocol. There are two main improvements in I-SA*. First, a node can now have multiple queues. This avoids problems related to querying priority during packet transmit phase. Second, the source node can transmit packets on another channel rather than waiting for the acknowledgement of previously transmitted packets. These two improvements result in an improvement of channel utilisation.

5.2.4 I-TDMA

Interleaved Time Division Multiple Access (I-TDMA) protocol [11] is a pre-allocation based protocol. It is a multichannel extension to the basic TDMA protocol. In this protocol, time is slotted on each channel. All nodes in the system are equipped with a tunable transmitter and a fixed receiver.. Some drawbacks of I-TDMA are that although it provides very high channel utilisation, it also offers high latency under light loads due to cycle synchronisation. It is also very inefficient in the support of variable-sized packets and suffers from the head of the queue problem because of the use of a single queue to buffer transmissions.

5.2.5 I-TDMA*

Interleaved Time Division Multiple Access* (I-TDMA*) is an enhancement [12] of I-TDMA. It is similar to the I-TDMA protocol, but eliminates the head of the queue problem that significantly impacts the performance of I-TDMA. I-TDMA* employs W transmitter queues at every node, where W is the number of data channels in the network.

In I-TDMA*, channels are pre-allocated for packet reception. Each node has one tunable transmitter and one fixed receiver. A source node tunes its transmitter to the channel of the destination node and transmits according to the access protocol. I-TDMA* avoids collisions by using time division multiplexing to access the channels. Throughput is considerably higher than in I-TDMA.

5.2.6 TDMA-C

The TDMA-Collisionless (TDMA-C) protocol [2] uses both the control channel and the data channel to transmit and receive packets. Each node maintains a status table that records the active status of each channel at the node. Each node has a tunable transmitter, a fixed receiver and a tunable receiver. Access to the control channel is based on a cyclic slot allocation scheme.

The major advantages of the TDMA-C protocol are support of variable sized data packets, and the absence of collisions on the control channel and the data channels.

Throughput is reasonably high.

5.2.7 DT-WDMA

Dynamic Time-Wavelength Division Multiaccess (DT-WDMA) [4] assigns each station a unique fixed wavelength for data transmissions, eliminating the possibility of collisions. There is one control channel shared by all the stations in the network, which uses time division multiaccess for broadcasting packet headers.

A station transmits the packet header on the control channel in its assigned time slot and follows this by transmitting the data packet on its unique data channel. All stations listen to the control channel. The station that is to be the destination, after listening to the packet header on the control channel, tunes its receiver to the corresponding channel to receive the data packet.

Destination conflicts occur when two or more stations transmit to the same destination at the same time. A global distributed algorithm is then executed to determine which packet to receive.

One fixed transmitter and fixed receiver are required by each node for the control channel, and a fixed transmitter and tunable receiver are needed for the data transmissions.

DT-WDMA can achieve respectable throughput (about 0.6), but the large amount of processing required for monitoring the control channel becomes a bottleneck as the number of stations in the network increases. Also, in order to retain bandwidth efficiency, either the length of the data packet or the bit rate of the control channel must scale in proportion to the number of nodes in the network.

5.2.8 Conflict-free DT-WDMA

DT-WDMA's destination conflict problem was solved by Chen and Yum, who developed Conflict-free WDMA [5]. This protocol uses reservations to schedule transmissions more efficiently, and in theory can attain a throughput of 1. However, this requires even more processing than DT-WDMA. Another disadvantage is that a station must wait at least one round-trip delay before transmitting a packet, eliminating the "tell-and-go" feature.

5.2.9 N-DT-WDMA

The significant processing requirements of Conflict-free DT-WDMA are reduced in N-DT-WDMA [18] by dedicating a control channel to each node. In this way, nodes only need to maintain information about the connections that they have with others, rather than all the connections in the network. The tell-and-go feature is retained, but destination conflicts are possible. N-DT-WDMA was the first WDM protocol to support different traffic classes in an attempt to integrate the MAC layer with the transport layer. The supported classes are connection-oriented with and without guaranteed bandwidth, and datagram traffic.

5.2.10 Dynamic Allocation Scheme

Dynamic Allocation Scheme (DAS) [6],[7] uses random scheduling algorithm to prevent collisions and destination conflicts. Like Conflict-free DT-WDMA, this protocol can realise a throughput of 1. One control channel is used to help coordinate the transmissions on the N data channels. The processing

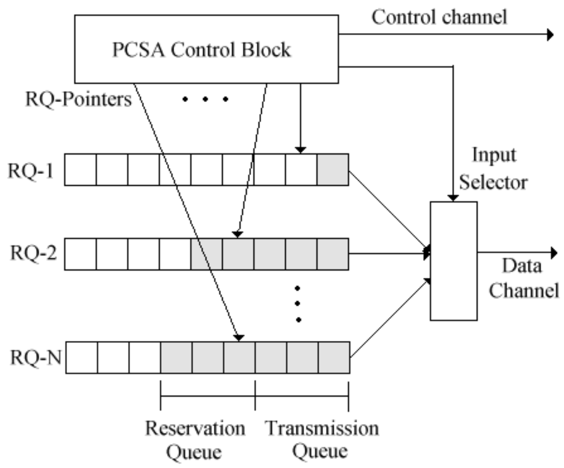

Figure 5.2: PCSA receiver queues in a single node

requirement of this protocol is high due to the scheduling algorithm and the monitoring of the control channel.

5.2.11 Pipelining Cyclic Scheduling Algorithm

The random nature of the DAS protocol's scheduling algorithm can produce erratic transmission delays. Also, the performance decreases as the ratio of the round-trip propagation delay divided by the packet transmission time increases.

Dinan and Gagnaire [10] developed the Pipelining Cyclic Scheduling Algorithm (PCSA) protocol in an attempt to ameliorate these problems.

Time is divided into slots, the size of which is the same for the control and data channels. The control slots are divided into N minislots, with one minislot assigned to each transmitter.

Arriving packets are stored in N separate buffers according to their destination. These N queues are called receiver queues.

Packet transfer is based on three stages: reservation, arbitration and transmission. In the reservation stage, stations reserve slots on a packet-by-packet basis. The PCSA control block, shown in Figure 5.2, has pointers that divide each receiver queue into a reservation queue (consisting of packets waiting for reservation) and a transmission queue (consisting of packets waiting for transmission). In the next stage, the arbitration algorithm based on cyclic scheduling is executed in all the stations — hence this protocol requires a large amount of processing. It is fair and guarantees that the receiver queue of a transmitter will be selected after at most N^2 slots.

Protocol	Equipment	Channels	Processing
Aloha	TT,TR	≥ 2	High
I-SA	TT,FR	≥ 1	Low
I-SA*	TT,FR	≥ 1	Low
I-TDMA	TT,FR	≥ 1	Low
I-TDMA*	TT,FR	≥ 1	Low
TDMA-C	TT,FR,TR	≥ 2	Very High
DT-WDMA	2×FT,FR,TR	$N + 1$	High
N-DT-WDMA	FT,TT,FR,TR	$2N$	Medium
Conflict-free DT-WDMA	2×FT,FR,TR	$N + 1$	Very High
DAS	2×FT,FR,TR	$N + 1$	Very High
PCSA	2×FT,FR,TR	$N + 1$	Medium

Table 5.1: Summary of MAC protocols for star topology

Protocol	Tell-and-go	Throughput	CA	DCA
Aloha	Yes	Low	No	No
I-SA	Yes	Low	No	Yes
I-SA*	Yes	Low	No	Yes
I-TDMA	Yes	Low	Yes	Yes
I-TDMA*	Yes	High	Yes	Yes
TDMA-C	No	Medium	Yes	Yes
DT-WDMA	Yes	Medium	Yes	No
N-DT-WDMA	Yes	High	Yes	No
Conflict-free DT-WDMA	No	High	Yes	Yes
DAS	No	High	Yes	Yes
PSCA	No	Medium	Yes	Yes

Table 5.2: Summary of MAC protocols for star topology. CA indicates Collision Avoidance protocols, and DCA indicates Destination Conflict Avoidance protocols.

Chapter 6

Bus Topology

There are two variants of the bus topology: the single-folded (or single) bus, shown in Figure 6.1, and the dual bus, shown in Figure 6.2. A single-folded bus topology with N nodes requires $2N$ individual 2×2 couplers whereas a dual bus requires $2N + 2$.

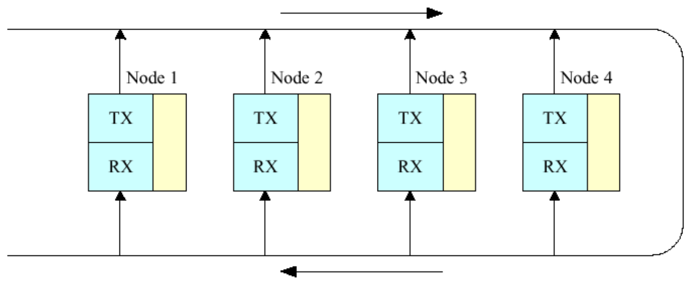

Figure 6.1: Single-folded bus topology with four nodes

Power losses in an optical bus network are proportional to the number of nodes in the network, so it is not widely used. However, the development of optical amplifiers has sparked renewed interest in bus topologies.

The bus topology is attractive for protocol design. Re-circulation of the optical signal is not possible, thus preventing the undesired effects caused by residual transmission caused by non-ideal optical filtering. Also, if time is divided into slots of fixed length, stations can transmit data without collision simply by sensing the transmission channel at the beginning of each slot period.

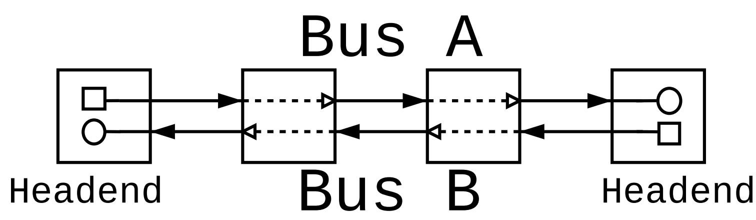

Figure 6.2: Dual bus topology with two nodes

6.1 MAC protocols

6.1.1 FairNet

The FairNet [1] medium access control protocol addresses this unfairness by using a probabilistic access mechanism that aims to provide an equal share of the bandwidth to all nodes.

In the FairNet architecture, each node has a fixed receiver, a tunable transmitter and a tunable sense tap.

Each node has a buffer separate buffer for each channel. When a packet arrives at node i for transmission, it is queued in a buffer corresponding to the channel it is to be transmitted on. Any number of data channels can be used, and there is no control channel. At the start of each slot boundary, node i randomly chooses a channel with probability p_{ic}. There is therefore a

$$1 - \sum_{c \in W} p_{ic}$$

probability that no channel will be chosen, where W is the number of channels. If channel c is chosen, node i will transmit the packet (if any) that is queued at buffer c if the slot is empty.

The channel selection probabilities can be modified to provide priority to nodes that demand a larger transmission probability, thus providing a limited form of QoS support.

6.1.2 WDMA

The wavelength division multiaccess (WDMA) protocol, developed by Lu and Kleinrock [22], is an extension of the single channel distributed queue dual bus (DQDB) [13] network to the multichannel case.

There are W wavelengths on each of the two buses, with channel λ_0 used as a control channel. For each bus, every node has a transmitter and receiver fixed at λ_0, and a tunable transmitter and receiver. Each slot on the control channel is divided into $W - 1$ minislots. A data channel is thereby uniquely identified by a minislot. Each slot also has an acknowledgement field consisting of W bits.

Nodes reserve minislots on the reverse bus and wait for the corresponding empty slots on the forward bus, as in the standard DQDB protocol. Upon transmission, the node assigns a timestamp to the control slot, and sets the busy bit and destination field. The node's tunable transmitter is then tuned to the wavelength of the channel identified by the minislot it just accessed, and the node transmits the packet at the beginning of the next slot. To receive, a node monitors the control channel. Upon seeing a slot with its address in the destination field, it tunes its receiver to the corresponding wavelength and receives at the start of the next slot. Destination conflicts are possible. These are resolved by accepting the packet with the oldest timestamp. Acknowledgements are sent by the headend to inform nodes of the outcome of their transmission.

WDMA has similar throughput performance to FairNet while achieving shorter average transmission delays.

6.1.3 nDQDB

The nDQDB protocol [19] is also a generalisation of the DQDB protocol to the multichannel case. It differs from WDMA in that it pre-allocates the transmission between senders and receivers and therefore does not require a control channel.

Like FairNet, nDQDB requires each node to have a tunable transmitter and a fixed receiver, where the receiver is assigned to a particular channel. Each node has a queue for each channel, and the DQDB protocol is run simultaneously on each channel.

Protocol	Equipment	Channels	Processing
FairNet	TT,FR	≥ 1	Medium
WDMA	2×FT,2×FR,2×TT,2×TR	≥ 2	High
nDQDB	2×FT,FR,TR	$N+1$	Very High

Table 6.1: Summary of MAC protocols for bus topology

Protocol	Tell-and-go	Throughput	CA	DCA
FairNet	No	Medium	Yes	Yes
WDMA	No	Medium	Yes	No
nDQDB	No	High	Yes	Yes

Table 6.2: Summary of MAC protocols for bus topology. CA indicates Collision Avoidance protocols, and DCA indicates Destination Conflict Avoidance protocols.

Chapter 7

Ring Topology

The ring topology (shown in 7.1) has become an attractive solution for all-optical local- and metropolitan-area networks. The problem of insertion losses at nodes between the sender and the receiver has been minimised by the recent development of optical amplifiers.

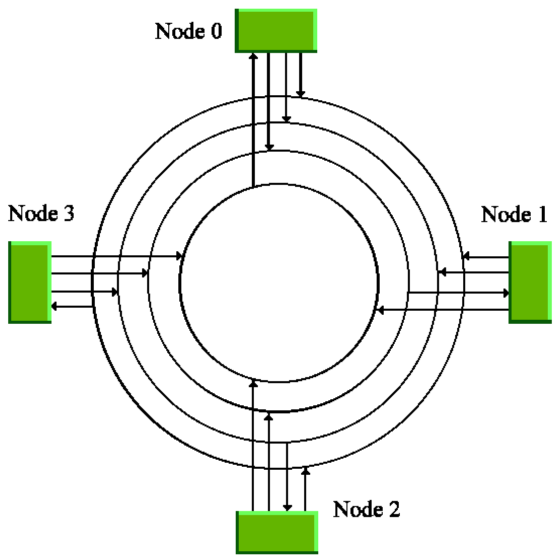

Figure 7.1: Logical network topology of a ring with four nodes

Rings have a number of desirable features. They allow slot synchronisation even at very high data rates, thus offering an efficient use of the optical bandwidth for packet communications. Two or more pairs of nodes in the ring can safely use the same wavelength simultaneously if their paths do not intersect. This wavelength re-use leads to higher throughput in heavy traffic conditions. Ring topologies have been proven to be efficient and survivable structures, able to tolerate one link failure.

7.1 MAC protocols

7.1.1 Token Passing

Under the multichannel token passing protocol [28], each node is equipped with W fixed transmitters and fixed receivers, where W is the number of channels. Tokens allowing transmission are passed around the ring in a round robin order. Only a small amount of processing is required at each node. This protocol is free of collisions and destination conflicts, but throughput is very low.

7.1.2 Request/Allocation Protocol

Request/Allocation Protocol [16] is a collision-free protocol. Time is divided into uniform slots. Each slot is divided into two sections: header and data. The header section contains N mini-slots, where N is the number of nodes in the network. The first minislot is used for clock synchronisation, and the remaining $N-1$ minislots are used to request and allocate bandwidth.

The data section is divided into M Data Minislots (DMSs). In order to transmit data, a node first requests a DMS and then waits for an allocation. For this reason, the protocol is referred to as Request/Allocation Protocol, or RAP. When a node receives multiple requests for bandwidth, it allocates DMSs in a round robin fashion until all of the requests, or all of the DMSs, are allocated.

7.1.3 Synchronous Round Robin

SRR or Synchronous Round Robin [24] is a collision-free protocol for ring networks where each node is equipped with a tunable transmitter and a fixed receiver.

It allows free access to the communications channels in light traffic conditions, and as traffic becomes heavier the protocol's behaviour becomes more like that of TDMA. This is an attempt to exploit the high throughput of TDMA under heavy traffic conditions with the short packet delays achieved by random access schemes under light conditions.

When used without a form of fairness control, SRR can lead to starvation of downstream nodes. SRR uses a fairness control algorithm based on Metaring [9]. Fairness in Metaring is attained by transmitting a control message named SAT (standing for SATisfied) that circulates around the ring. Nodes are granted a quota for the maximum number of packets allowed to be sent until they receive the SAT message again. Each node normally forwards the SAT message without delay. However, if a node has packets to send and has not reached its quota, it retains the SAT message until it reaches its quota or sends all of its packets.

7.1.4 SR^3

Synchronous Round Robin with Reservations (SR^3) [23] is an enhanced version of SRR that allows nodes to reserve slots, thus providing tighter control on access delays. It is therefore well suited to providing support for traffic classes with different QoS requirements.

SR^3 provides very good performance for guaranteed quality traffic, and also improves on the performance of SRR for best-effort traffic.

7.1.5 Reservation/ACK/Transmission Protocol

This protocol is designed for use in a ring network where each node is equipped with a wavelength add/drop multiplexer (WADM).

A WADM is a device that selectively adds, drops or passes through optical signals according to wavelength. They may be classified as static or dynamic. A static WADM can only add or drop pre-assigned wavelengths. It therefore has no switching function and cannot provide protection against network faults or provide flexibility in routing. A dynamic WADM is capable of adding and dropping wavelengths dynamically at each node according to the network's management.

WADMs can be further classified as serial or parallel, although there are possible hybrids. Serial WADMs generally involve traffic disruption if they are reconfigured. A parallel WADM, shown in Figure 7.2, consists of a demultiplexer, a number of add/drop switches, and a multiplexer. Each add/drop switch has add/drop mode and pass mode.

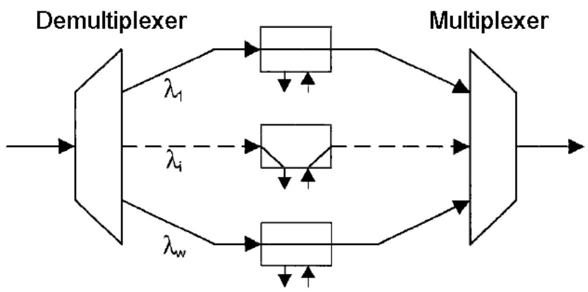

Figure 7.2: Structure of a parallel wavelength add/drop multiplexer

Since intermediate nodes between the sender and receiver must not add or drop the wavelength being used, the state information of wavelengths and add/drop switches at each node must be exchanged. There are W wavelengths, and these are shared by all the nodes in the network. The wavelengths are partitioned into one control channel, λ_0, and $W-1$ data channels. Since all nodes must send and receive control information, the add/drop switch corresponding to the control channel is fixed in add/drop mode.

In this protocol, each node that wishes to transmit must reserve a wavelength that was unreserved until now, and wait until the destination node receives acknowledgement that it will be a receiver, hence the name of the protocol.

The structure of the control and data frames are shown in Figure 7.3. Each frame begins with several bits that are used for clock synchronisation, followed by a miniframe for each data channel. The miniframes store information on the allocation of wavelengths in the network and consist of four fields: Flag, Reservation, First Node (FN), and ACK. The Flag field is a single bit that is set to 1 if the wavelength has been reserved by some node. Reservation and ACK fields indicate which nodes will drop the data frame from the wavelength. Both fields require N bits, where N is the number of nodes in the network.

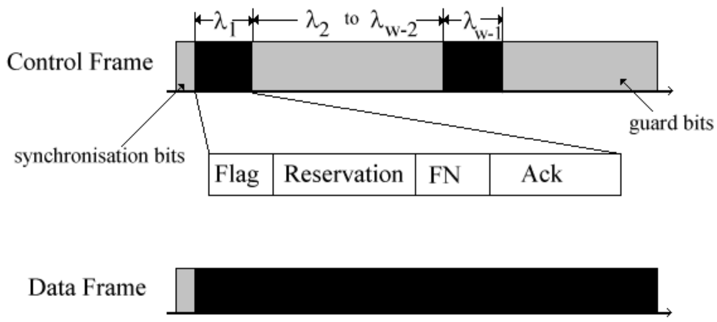

Figure 7.3: Structure of control frame and data frames used in the RATP protocol

The Reservation field refers to nodes that reserved the wavelength in the current slot period, whereas the ACK field deals with the previous slot period. The ACK field is therefore the same as the Reservation field of the previous slot period. Its purpose is notify destination nodes that they will need to drop the data frame that will be sent on that wavelength. FN records the number of the first node that reserves the wavelength. This requires $\lceil \log_2(N+1) \rceil$ bits.

In the reservation stage, each node tries to reserve a wavelength if it has a packet to transmit.

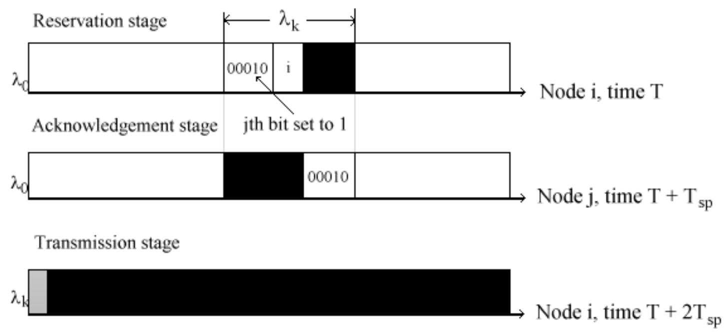

Figure 7.4: The three steps of the RATP protocol: reservation, acknowledgement and transmission

The bits set in the Reservation fields are moved to the ACK fields in the Acknowledgement stage (see Figure 7.4), because each node must know if it is going to be the receiver in the current slot period.

Finally, the packet is transmitted on the wavelength reserved in the reservation stage.

Protocol	Equipment	Channels	Processing
Token Passing	$W\times$FT,$W\times$FR	≥ 3	Low
SRR	TT,FR	N	Medium
SR^3	TT,FR	N	High
RAP	WADM	N	Medium
RATP	WADM	≥ 2	Medium

Table 7.1: Summary of MAC protocols for ring topology

Protocol	Tell-and-go	Throughput	CA	DCA
Token Passing	No	Very Low	Yes	Yes
SRR	No	High	Yes	Yes
SR^3	No	High	Yes	Yes
RAP	No	Medium	Yes	Yes
RATP	No	Medium	Yes	Yes

Table 7.2: Summary of MAC protocols for ring topology. CA indicates Collision Avoidance protocols, and DCA indicates Destination Conflict Avoidance protocols.

Chapter 8

Simulations

The PCSA and RATP medium access protocols were simulated with Akaroa2 [15], a simulation controller capable of running stochastic simulations in parallel on multiple computers. Akaroa2 runs such simulations until it attains the level of relative precision and confidence level specified by the user. In this manner, Akaroa2 gives the user control over statistical errors. For each experiment, relative precision of 0.05 and confidence level of 95 percent were specified. To guard against terminating the simulations prematurely, each experiment was repeated 5 times, and the longest of these replications was recorded.

For both protocols, the simulated traffic consisted of Poisson packet arrivals. The destination of each packet was randomly selected. It was assumed that a node does not send data to itself.

The simulated star and ring topologies both consisted of 8 nodes, and used 9 wavelengths. The transmission capacity of each simulated network was 1 gigabit per second, and 4 bits were used by each frame for clock synchronisation.

Chapter 9

Results

9.1 Pipelining Cyclic Scheduling Algorithm

PCSA is a naturally collision-free protocol since no two nodes can use the same wavelength for data transmission. Also, the scheduling algorithm guarantees that contention at receivers is avoided. These two factors help increase throughput by ensuring that packets never need to be resent.

We observe from Figure 9.1 that PCSA is capable of achieving a throughput of 1.

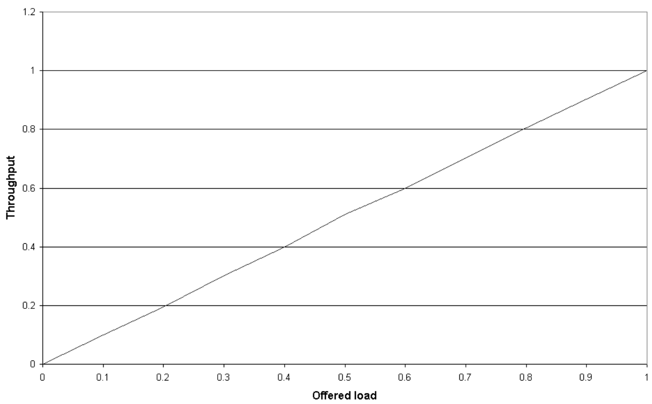

Figure 9.1: Throughput versus offered load

However, at high offered loads the average packet delay increases rapidly, as shown in Figure 9.2. Nevertheless, PCSA achieves very good packet delays under light traffic loads.

The relationship between the physical network size and packet delay can be observed in Figure 9.3. Link length refers to the length of optical fibre between

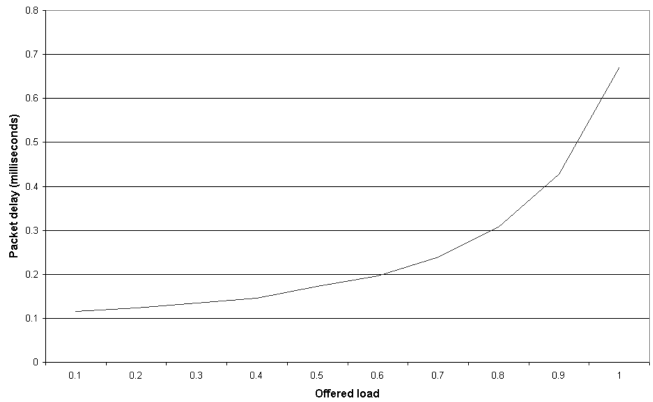

Figure 9.2: Packet delay versus offered load

a node and the central coupler. We see that average packet delay grows linearly with the increase in network size.

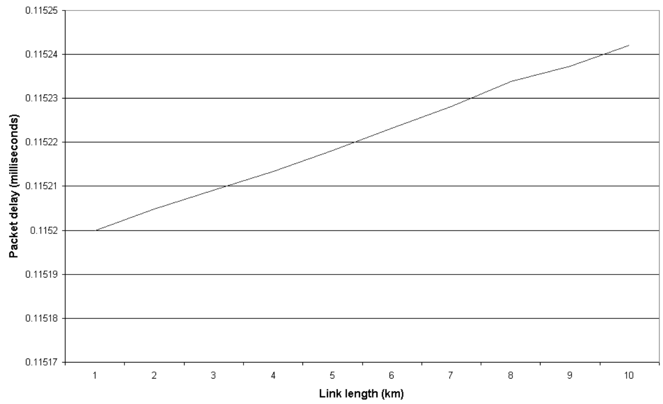

Figure 9.3: Packet delay versus network link length

9.2 Reservation/ACK/Transmission Protocol

Figure 9.4 shows how the throughput achieved by ring networks of size 1 kilometre, 10 kilometres and 20 kilometres changes with the offered load. It can be seen that the rate of increase of throughput decreases as the offered load increases. The 1 kilometre network achieved a respectable maximum throughput of almost 0.65. However, the throughput performance of the larger networks was considerably poorer.

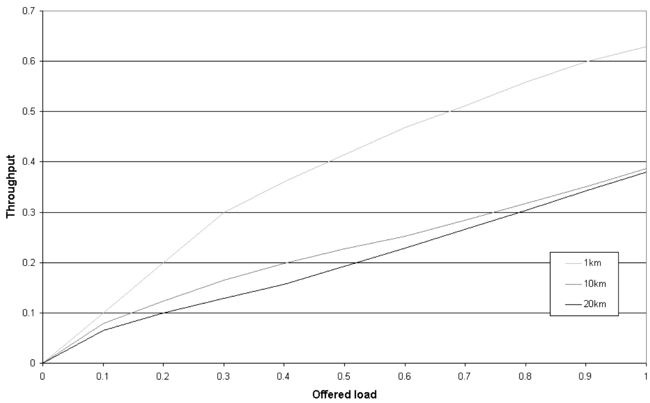

Figure 9.4: Throughput versus offered load for rings of size 1km, 10km and 20km

The average packet delay of the aforementioned networks is shown in Figure 9.5. Again we see that the larger networks have considerably poorer performance. F

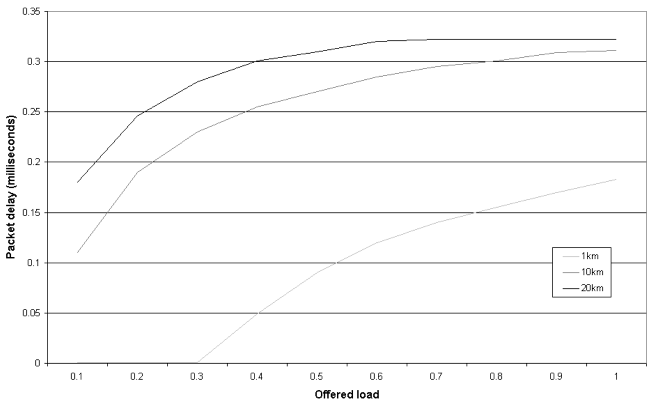

Figure 9.5: Packet delay versus offered load for rings of size 1km, 10km and 20km

Figure 9.6 illustrates the need for fairness control in RATP. The downstream nodes find that the upstream nodes have already reserved wavelengths, leaving fewer wavelengths available. The upstream nodes therefore have a greater probability of successfully transmitting their packets in a given slot period. For

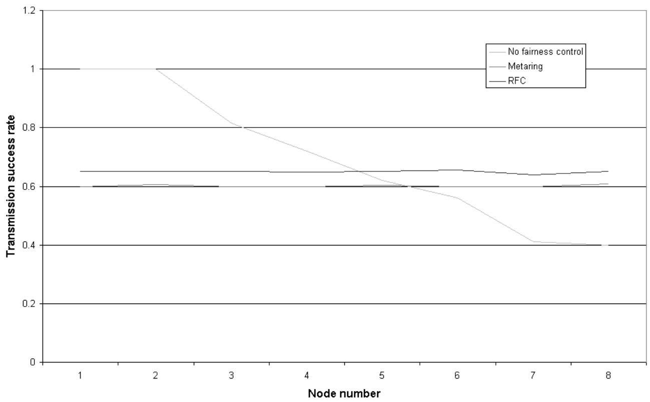

Figure 9.6: Transmission success rate for each node in the network

this fairness control testing, the ring size is 1 kilometre, offered load is 0.8 and transmission quota is 10 packets.

The effect that the fairness control options have on throughput is shown is Figures 9.6 and 9.7. It can be seen that although RATP with no fairness control leads to starvation of the downstream nodes, the increased transmission activity of the upstream nodes makes the overall average throughput slightly higher than when using either fairness scheme. RFC delivers throughput performance superior to Metaring's since nodes that have reached their transmission quota since the last SAT token visit are allowed to send their packet if they can safely reuse a wavelength.

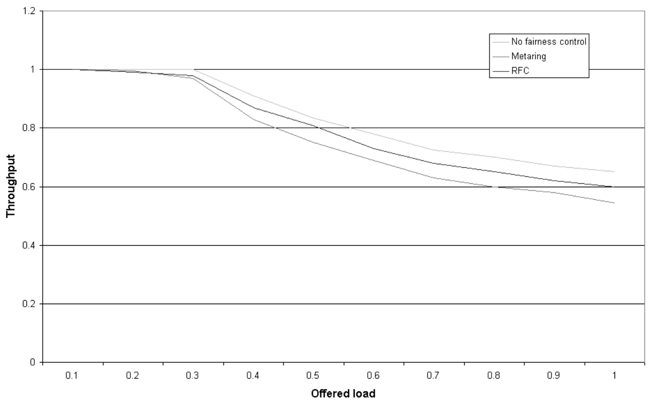

Figure 9.7: Throughput versus offered load for RATP without fairness control, with Metaring, and with RFC

Chapter 10

Conclusions

The explosive growth of data traffic has produced an acute need for high-speed networks. Fibre-optic technology, with its incredible bandwidth, promises to meet this demand with ease. Wavelength division multiplexing, which allows transmission on several wavelengths simultaneously, is currently the leading method of utilising the bandwidth of optical fibre.

WDM line systems are already used throughout the world, and attention is now turning to WDM local and metropolitan networks.

The star topology is currently the most popular WDM network topology, partly due to its low signal losses. The development of optical amplifiers that can compensate for these losses has revived interest in the bus and ring topologies. Rings have a number of advantages, including slot synchronisation at very high data rates, increased throughput via wavelength reuse, and ability to handle a link failure.

The performance of the star protocol PCSA and the ring protocol RATP was evaluated by stochastic simulation. PCSA was found to be able to achieve a throughput of 1, and under light traffic conditions the average packet delay is small. The throughput is not significantly impacted by the physical size of the network, and packet delay was found to increase linearly with the length of fibre used.

In contrast, RATP's throughput and delay are both heavily degraded by by increases in the network size, making it best suited to local area networks. RATP can achieve a good throughput rate of 0.65 on a 1 kilometre ring network.

MAC protocols that use scheduling algorithms to avoid collisions and destination conflicts deliver high throughput in heavy traffic conditions since there is no need to re-transmit packets that did not reach their destination. However, scheduling algorithms increases complexity and eliminates the tell-and-go feature, whereby a node does not wait before transmitting a packet.

With the rapid advances in computing speed, it is becoming more feasible to implement more complex MAC protocols in order to improve efficiency.

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